AFRL-SR-AR-TR-07-0522

REPORT DOCUMENTATION PAGE

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
07-11-2007	Final	02/15/2002-06/30/2007

4. TITLE AND SUBTITLE
Advanced Concepts in Space Situational Awareness

5a. CONTRACT NUMBER

5b. GRANT NUMBER
F49620-02-1-0107

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Sudhakar Prasad and David Tyler

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of New Mexico
Contract and Grant Accounting
MSC01 1245
1 University of New Mexico
Albuquerque, NM 87131

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific
Research/NM
875 N. Randolph St., Rm 3112
Arlington, VA 22203
Dr William Hilbun/NL

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR/NM

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Unlimited Approved for public release. Distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report covers the technical accomplishments of the project entitled "Advanced Concepts in Space Situational Awareness" over the period Feb 15, 2002 - June 30, 2007. The report contains a summary of the activities, accomplishments, and research/technology transitions of the project followed by their detailed technical description. Important original advances were made in the areas of information theoretic image assessment, algorithm development, spectral data mining, polarimetric imaging, and large-scale linear and nonlinear optimization methods. Applications of these advances to a number of areas of interest to the AF community are possible and some demonstrated, including the use of spectral data mining and polarimetric imaging for SOI, information-optimized imaging system design, computationally efficient and powerful processing methods for SSA data. A number of technology transitions that resulted attest to the success of the project, including information theoretic analysis for image evaluation, physically constrained image deconvolution (PCID) algorithms transitioned to MSSS, and spectral unmixing algorithms based on non-negative matrix andtensor factorization for rapid SOI.

15. SUBJECT TERMS
Space situational awareness, information theory, image processing, polarimetric imaging, spectral data processing, algorithm development, space object identification, adaptive optics

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Sudhakar Prasad
UU	UU	UU	Unlimited	23	19b. TELEPHONE NUMBER (include area code) 505-277-5876

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Final Report for
AFOSR Grant F4960-02-1-0107
Advanced Topics in Space Situational Awareness

Sudhakar Prasad, PI
Center for Advanced Studies and Dept of Physics and Astronomy
University of New Mexico
Albuquerque, NM 87131
sprasad@unm.edu

1 Overview

This grant was a five-year, multi-institution Partnership for Research Excellence and Transition (PRET). The goals of the grant were 1.) original research in a variety of areas of interest to DoD's space surveillance mission, 2.) transition of research results to the Maui Space Surveillance Site, and 3.) enhancing the research environment on Maui. These project goals were well achieved, as discussed in this report. After listing the Core Activities and Personnel for this grant, we describe all of the project accomplishments, including original research results, original publications, invited presentations, and technology transitions.

2 Core Activities

The following were the regular core activities of the grant:

- Research programs at the University of Arizona, the University of New Mexico, the University of Hawaii, and Wake Forest University. Research was also conducted in collaboration with the Oceanit Laboratories on Maui, AFRL/DEBI, and at the Innovative Science and Technology Experimentation Facility (ISTEF).

- Maui visitor program. The grant paid for visiting researchers to give colloquia and short courses, as well as longer collaborative research visits. The purpose was to inform resident researchers of emerging research and development in space surveillance concepts and thus inspire new opportunities for collaboration.

- The Maui Scientific Research Center (MSRC), Stuart Jefferies, Director. The MSRC was a locus for on-island grant activities, technology transition to the Air Force Maui O&M contractor, and NSF and NASA solar physics research programs. Since 2006, following the closure of MSRC upon Dr. Jefferies' acceptance of a professorial appointment at the Institute for Astronomy (IfA) at the Univ. of Hawaii, Kula, Maui, Maui based research under the project has been performed at the IfA. Prof. Jefferies was actively assisted in his researches by Dr. Doug Hope, now an assistant professor at the IfA.

3 Funded Senior Personnel

- Dr. Sudhakar Prasad, Professor, Dept. of Physics & Astronomy, University of New Mexico (PI)
- Dr. David W. Tyler, Research Associate Professor, Optical Sciences Center, University of Arizona (co-PI)
- Dr. Stuart M. Jefferies, Professor, IfA, University of Hawaii (Co-PI)
- Dr. Robert J. Plemmons, Reynolds Professor of Mathematics & Computer Science, Wake Forest University
- Dr. Todd C. Torgersen, Associate Professor, Dept. of Computer Science, Wake Forest University
- Dr. Douglas Hope, Assistant Professor, IfA, U. of Hawaii.
- Mrs. Kathy J. Borelli, KJS Consulting, Haiku, Maui, HI

4 Summary of Project Accomplishments

The project accomplished a number of important objectives over its five-year duration, specifically to

- establish the importance of fundamental research for generating new technologies and development concepts in SSA;
- enhance the research environment of AMOS/MSSS by bringing in a number of distinguished research scientists from around the world to AMOS;
- raise the awareness of the excellent facilities available at AMOS for conducting imaging and nonimaging research and data analysis;
- transition advanced mathematical concepts and software resulting directly from the original research performed under the project; and
- educate and train a new generation of scientists to carry on SSA research.

The following list contains a quick numerical summary of the project accomplishments and deliverables:

- No. of refereed publications – 27
- No. of unrefereed publications – 24
- No. of invited conference presentations – 40
- No. of contributed conference presentations – 28
- No. of leveraged grants – 14 (total amount – $7.75M, including $3.66M on Maui)
- No. of research/technology transitions at AMOS/MSSS – 4 (government investment: > $3M)

5 Detailed Research Accomplishments

A number of original research investigations were enabled by the PRET grant funding. Below we describe in some detail each of these investigations, their important results, and how they impact AF's SSA objectives.

5.1 Noise transport

Dr Tyler, Prof Prasad, and Dr. Doug Hope[1] worked on a modification of the Richardson-Lucy deconvolution algorithm to estimate an object's energy spectrum from partially-compensated adaptive optics image data. Noise transport and scaling concepts as developed by Matson, Tyler, and Prasad, were used in this new algorithm. This was shown to have significant application in the detection of very faint "companion" point sources to the AO reference source. This has obvious application to SSA in terms of detecting faint objects in the close vicinity of a more brightly lit satellite. While no new refereed paper resulted from this work, two conference presentations were made by Dr. Tyler during the year 2002, including one at the IAU conference on Brown Dwarf objects.

5.2 Adaptive Optics

Dr Jefferies continued his multi-conjugate adaptive optics (MCAO) research collaboration with the University of Arizona. This work resulted in a very important paper [13], one of many highlights of the PRET activity, that was published in Applied Optics (with Michael Lloyd-Hart and Keith Hege of Arizona). It reported on results from experimental scintillation compensation using phase diversity. These results showed phase diversity can be used to compensate scintillation as well as phase aberrations resulting from atmospheric turbulence. They also demonstrated the feasibility of using phase diversity in an AO wavefront sensing scheme by using deliberately undersampled detector planes.

Dr Tyler modeled modal filtering of the AEOS AO system using singular-value decomposition of the reconstructor matrix. He showed that the modal filtering concepts used in low-order AO systems such as ESO's COME-ON+ and CFHT's *Pueo* and *Hokupa'a* are also viable for high-order systems like AEOS. Dr Tyler also showed that that shape of the mode filter can affect the shape and energy distribution of the resulting compensated point-spread function, perhaps allowing reconstructor customization for such applications as spectroscopy.

5.3 Information Theoretic Assessment of Image Formation, Detection, and Post-Processing

Prof Prasad began with new theoretical calculations for the limiting values of Shannon information capacity of an imaging system as a function of atmospheric turbulence severity. For various classes of objects, these calculations allow quantitative determination of the fundamental limits to inverse imaging methods. He also used a Richardson-Lucy algorithm to analyze the recovery of information in turbulence-degraded imagery as the algorithm iteratively processes image data. His results

[1] Dr. Hope was a graduate student of Prof Prasad's and participated in grant activities during the period 2002-2005. However, the main support for his PhD work was derived from his prestigious JPL/NASA funded Michelson Fellowship

include information recovery beyond the classical diffraction limit, or "super-resolution." Such optical superresolution is characteristic of many model-based image processing algorithms, and reflects the incorporation of additional information implicit in the use of *a priori* model or constraint into the final reconstructed image.

Subsequent work in this area was concentrated in three different areas: 1. Fisher information-based optimization of integrated imaging systems, particularly phase-diverse speckle imaging systems; 2. Use of pupil-phase engineering (PPE) for optimization of integrated imaging systems, particularly to achieve well-optimized extended-focus and aberration-corrected imaging systems; and 3. Derivation of fundamental information-theoretic results on the performance of imaging systems. Significant progress was made in each of these areas, as evidenced by a number of publications and presentations. The PPE projects involved a collaboration across three different institutions, U. New Mexico, Wake Forest U., and an optical engineering consultant. In addition to the funding from this grant, the PPE research also received support from the ARO and the government intelligence community.

Using information theory, Prasad was able to calculate detailed expressions for the amount of information transmitted by a phase-diverse speckle (PDS) imaging system. He also demonstrated by means of these calculations that information acquired in the second (phase-diverse) data channel may not depend critically on the actual form of the "diversity" phase. For example, the most common PDS configuration is two cameras; one in-focus and the other deliberately defocused by some amount. The diversity phase in this case is then a quadratic defocus. In any realizable PDS system, however, the optical paths to the two cameras will differ by more than the simple defocus: Other "non-common path" errors will exist in practice, so this result has significant consequence for practical use of PDS.

Prasad subsequently used Fisher Information based (FI) techniques to perform an analysis of the minimum error associated with estimation of the accuracy of finding the center of a point-spread function (the image of a point source, like a star) in the presence of photon noise and a constant sky background. This is critical for the error analysis of astrometric instruments like the 8-m Large Synoptic Space Telescope, planned to survey large regions of the sky for space debris and objects in order to track them. The analysis also has clear relevance to the SSA task of precision orbit determination using ground-based telescopes. A second FI based analysis was carried out to derive the minimum possible error for estimation of relative intensity and separation of a faint companion to a bright stellar source. While this work has obvious relevance to extrasolar planet detection, it also applies to estimation of faint features on orbiting objects when images of the object are dominated by bright glints. These studies were presented in invited lectures at the SIAM Image Science meeting held in Minneapolis May 15-17, 2006 and at the 10th Summer Synthesis Imaging Workshop sponsored by the National Radio Astronomy Observatories (NRAO) at the University of New Mexico (2006).

Information theoretic evaluations were further extended to the problem of wavefront coding and image superresolution. Prasad computed the detailed dynamics of Fisher information as a function of the strength of wavefront coding for the specific application of extension of image depth well beyond what is possible in a standard imaging system. The problem of optical superresolution was also tackled on the same footing of Fisher information, and theoretical predictions made by Matson and Tyler [21] for the case of support-constrained imagery were confirmed and extended by Prasad in work that has been submitted for publication [40]. Two invited presentations resulted from these two investigations in 2007, one at OSA's Computational Optical Sensing and Imaging

(COSI) meeting and another at SPIE's Unconventional Imaging conference in San Diego.

5.4 Digital and Optical Super-resolution

The ability to extrapolate information meaningfully to spatial frequencies outside the pass-band of the overall imaging system is limited largely by the prior information available. At the optical level, the largest measurable frequencies are limited by diffraction and system noise; while at the digital level, it is the detector pixel size and detector noise that limit the highest measurable frequencies. When the latter provides the limiting passband, the use of a sequence of sub-pixel-shifted images of the same scene can be exploited to recover image information at the sub-pixel resolution. A generalized sampling theorem (GST) furnishes the fundamental basis for such digital super-resolution. Prasad completed a theoretical analysis of the essential connection between GST and digital super-resolution in a paper recently published by JOSA-A [39]. With Torgersen, Prasad also performed an extensive application of Fisher information theory and related estimation theoretic noise bounds to the reconstruction of super-resolved imagery. We have found that the noise amplification and its propagation across the image during reconstruction can be quite severe, and regularized reconstruction approaches that implement sensible prior information are critical to reliable super-resolution.

A complete characterization of the "primary" and "secondary" components of optical super-resolution was performed under a collaboration [21] with Dr. Charles Matson (AFRL). This effort was directed at a quantitative assessment of the potential of super-resolution concepts and algorithms. Secondary super-resolution can be thought of as generation of spectral components beyond the classical diffraction cutoff, but biased or otherwise meaningless relative to the "truth" object being estimated. This work was based on some previous work and ideas that Matson had already developed and published, and it has already attracted much positive attention in the research community.

Using the same Fisher-information theortic approach Prasad extended this research to more general PSFs than the coherent PSF for which Matson and Tyler derived their results. This research was mentioned earlier in the report.

5.5 Adaptive aperture imaging

Dr Tyler formed a collaboration with Dr Olivier Lai from the Canada-France-Hawaii Telescope (CFHT) to study innovative fixed pupil geometries in addition to real-time adaptive pupil masking. They presented results at the August 2002 SPIE Conference on Astronomical Telescopes and Instrumentation.

5.6 Wavefront phase encoding

Profs Plemmons, Prasad and Torgersen developed computational methods associated with wave front phase encoding and decoding for image quality control in optical-digital imaging systems. The purpose was to remove certain aberrations, such as defocus, that degrade the collected image. The depth-of-focus of an imaging system is the distance in the object space over which objects are considered to be in focus. One approach to this problem that has been studied over the past decade is to insert a cubic phase mask directly into the optical-digital system in order to increase the focus invariance of the point spread function by wave front coding. Current extended focus methods primarily involve wave front phase encoding by using cubic phase mask with a single design parameter, followed by digital filtering to decode the phase. They are now analyzing a new approach to the problem of removing aberrations, based on a multiple-parameter optimization scheme. This approach involves the use of the largeness of the Strehl ratio and the smallness of its derivatives with respect to a defocus parameter as markers for determining the optimal pupil-phase distribution for which image quality is highly insensitive to focus errors. A number of papers [6,28,29,30,31,32,33,34,35] on this general pupil-phase engineering approach were published during the grant period.

Applications of this research may include not only enhancing laser guide star AO for SSA but also facial recognition methods for anti-terrorism surveillance.

5.7 Advanced algorithm development

Dr Jefferies and Mrs. Borelli developed a blind deconvolution algorithm [22,23] for imaging through turbid media, such as a thin cloud or sea water layer. They modified the algorithm to simultaneously estimate the scattered background light; prior to this development, the background scattered light had to be measured separately from the program object to provide a calibration data. Mrs. Borelli worked on a parallel version of this code. Iterative codes such as blind deconvolution are inherently difficult to parallelize, unlike "direct" (single step) algorithms, so this presented a major challenge.

An outstanding difficulty of wavefront recovery in usual blind deconvolution algorithms had to do with the sign ambiguity in the relation between even-order wavefront aberrations and PSF morphology; that is, even-order aberrations of different signs (consider defocus) yield indistinguishable PSFs. Thus, while blind deconvolution algorithms can be used to estimate both the object and PSF, they had not previously been used to estimate the wavefront aberrations associated with the PSF. However, by exploiting the fact that low-amplitude, high-frequency PSF "halo" speckles are caused by higher-order phase aberrations with little ambiguity, Jefferies developed and demonstrated a new algorithm that accurately solves for the wavefront as well as the object. The new algorithm also makes relies heavily on previous work by Jefferies to incorporate atmospheric temporal evolution constraints in PCID.

A key part of our research has been the development and modification of reconstruction algorithms such as the PCID "blind" deconvolution code. In 2001-2005, the PCID algorithm was extensively modified [14,15,23,24,25,26,27] by Jefferies and Borelli and parallelized using software techniques developed by Borelli under the PRET high-performance computing research program. Hope further modified PCID to estimate Fourier spectrum components rather than image-domain pixel energies and to constrain the spectral estimates according to estimates of the measured SNR. With Jefferies, Keith Hege of the University of Arizona's Steward Observatory, and Borelli, Hope used the modified PCID code and data from the University of Arizona's AO-compensated 6.5-m MMT telescope to produce diffraction-limited imagery of a Canadian Anik-F2 communication satellite in geostationary orbit. The satellite was observed at a range of over 23,000 miles. This image is, as far as we know, the first-ever direct image of an Earth-orbiting satellite so distant. The images demonstrate again the synergy of adaptive optics and image processing algorithms. The data was collected at 1.6 μm by Drs Michael Lloyd-Hart and Phil Hinz of Steward.

Tyler and Borelli [2] incorporated a support constraint in a bispectrum phase estimation algorithm. A theoretical expression for the variance of the bispectrum phase is evaluated in the new code before and after support is applied; if the noise is higher after the constraint is applied, the original (unconstrained) data is used. This technique required significant modification of the existing bispectrum code. Use of the new algorithm results in a bispectral phase with reduced noise. The object phase spectrum calculated from the reduced-noise bispectrum also had reduced noise. The actual amount of noise reduction was quantified in this study.

Plemmons worked with Jefferies and Prof. Jim Nagy (Emory University) on an algorithm to deblur image data corrupted by a field-varying blur function. Conventional deconvolution approaches all assume a field-invariant point-spread function (PSF), forming a Fourier transform pair with the Optical Transfer Function (OTF). If the blur function varies over the image field, the OTF and PSF are undefined, and novel techniques must be used. Plemmons' group sectioned the field into isoplanatic patches (fields over which the blur is invariant) and used phase diversity and an assumed correlation between patches to solve for the space-varying blur. Test results on simulated star cluster data showed the technique to be effective.

Plemmons and Jefferies (with Jonathan Bardsley of the University of Montana and James Nagy of Emory University) refined and extended this work [8,26]. The innovation of the refined method is that, rather than restoring the local patches individually and then interpolating the patches to obtain the final image, a "global" blur function was obtained by interpolating the local PSFs. The global blur function was then used to restore the full image using previous work by Nagy and Diane O'Leary of the University of Maryland. This new approach can be expected to provide better image quality because while the blur function may be shown to vary smoothly over the field, images generally do not. This work was demonstrated using a synthetic "crowded" star-field image in a publication.

5.8 Summer Faculty Visits to Maui

Profs. Prasad, Plemmons, and Torgersen spent two weeks, July 11-23, at the Maui Scientific Research Center. Prof. Pa'ul Pauca (Wake Forest) also visited. The visits were planned to provide collaborative opportunities and workshop participation. At an AFRL-Boeing workshop on Information Theory and Imaging Applications, Prasad presented a talk on the subject of Parseval-type sum rules he recently derived for information in signals. He also finished a manuscript reporting these results during his visit, and will submit the paper to JOSA-A. Plemmons worked on non-imaging space-object identification (SOI) with Maile Giffin, Curt Leanard, and Dan O'Connell (Oceanit) and Kris Hamada (Boeing). New information-theoretical data clustering techniques were developed and tested, and two presentations (one oral and one poster) were prepared for the AMOS Technical Conference. Torgersen worked on analysis techniques for the cache of phase-diverse speckle (PDS) imaging data collected by Tyler and Seldin on the GEMINI telescope. He also worked with Stuart Jefferies on the use of constraints on temporal atmospheric evolution in "blind" deconvolution algorithms. Finally, Mr. Muralimanohar and Mr. Murali visited Maui for three weeks this summer to assist with setup and characterization of the S-Cube simulator, described briefly below.

5.9 Data Mining of Spectroscopic Satellite Observations

Research in this program addresses two aspects of non-imaging space object identification (NISOI). The identification and classification of space objects that cannot be resolved with currently available ground-based telescopes is an important but difficult problem. While adaptive optics technology has been able to produce high-resolution images for a variety of low-Earth-orbiting (LEO) objects, even very large satellites in highly elliptical or geosynchronous orbits are so far away as to be unresolvable from the ground. In addition, new technology means foreign SIGINT and MASINT satellites in LEO orbits are becoming smaller and more difficult to image. One interesting and promising approach to circumvent the imaging limitation is to collect wavelength-resolved spectral reflectance data on such satellites. The spectra can then be used to determine information such as material composition of an object. Current work has been focused on the determination of material composition (fractional abundances) from spectral traces when the types or classes of composing materials are known *a priori*. We extended previous work to determine not only fractional abundances, but also the classes of composing materials that make up the object. We employ non-negative matrix factorization algorithms for unmixing of spectral reflectance data and regularized inverse problems methods for determining corresponding fractional abundances. We are using for both simulated and observed spectral data obtained with the Spica spectrometer on the MSSS GEMINI telescope. Information-theoretical techniques involving the generalized Kullback-Liebler measure have been developed and applied in this work.

Plemmons (with Paul Pauca at Wake Forest and Kira Abercromby at NASA JSC) continued research and development of spectral unmixing algorithms for use in non imaging space object identification (SOI). Broadly, the algorithms exploit constrained matrix factorization methods after pre-processing the data with wavelets. Real data from the AMOS SPICA system and from NASA confirmed the utility and robustness of the algorithms. Based on this pioneering work, Plemmons, et al., published a number of spectral unmixing papers [7,9,10,11,12]. Plemmons also gave a number of invited talks on this topic, including one at the Technion in Haifa, Israel where he continues a collaboration with computer science faculty.

Plemmons also developed a new approach [17] to SOI data mining. The technique is based on tensor factorization methods and k-means clustering, and can be used for both imaging and non-imaging data. The key idea is to treat hyperspectral data as 3-D arrays and to factorize those arrays into sums of rank one tensors that can be used for object identification and clustering. Like NMF methods, this technique typically outperforms PCA-type methods. Plemmons presented a number of talks on this work, including one at the Stanford Conference on Algorithms for Analyzing Modern Massive Data Sets in 2006. Initial testing on real satellite imagery provided by Borelli and spectral data provided by NASA have confirmed the potential of this novel new technique.

5.10 GEMINI imaging system detector analysis

Dr Tyler and both his students, along with Kathy Borelli, analyzed data from the GEMINI telescope system on the AMOS 1.6-m telescope. Analysis of the data proved a time-varying detector bias was leading to residual energy spectrum bias when using Labeyrie's technique for energy spectrum estimation in the presence of atmospheric turbulence. The results of this work were published [18] in the Proceedings of the Astronomical Society of the Pacific.

5.11 Phase Diverse Speckle (PDS) Imaging

PDS is a two-camera system allowing joint estimation of the object and realizations of resolution-degrading turbulence from a sequence of short-exposure images, acquired simultaneously by both cameras. As mentioned earlier in the report, Prasad derived important Fisher-information-based metrics of design and performance of the PDS system. Specifically, he calculated FI based expressions [4,5] for the best lower bounds on the error variance of estimating an object from its phase diverse image data as a function of the strength of atmospheric turbulence, parameterized by the ratio D/r_0. This was used to demonstrate, e.g., an optimal value of the defocus of the phase-diverse data channel for which that channel adds maximum information to the data acquired by the in-focus channel.

Much work was also devoted to the analysis of PDS data acquired at the MSSS 1.6-m GEMINI telescope. The data were collected at a variety of defocus values and for several binary star pairs. Reduction of this data, already complete, and its analysis will allow experimental validation of the information- theoretical analysis (Prasad) of the optimal PDS defocus. In addition, Jefferies and Torgersen worked on a way to constrain reconstructed imagery based upon *a priori* knowledge of the temporal statistics of atmospheric turbulence.

Dr Tyler and Prof Todd Torgersen also conducted a simulation study [20] of Zernike mode estimation using phase-diverse speckle (PDS) imaging data. The data was simulated using a model of the GEMINI PDS system developed by Dr Tyler and reduced using code written by Dr Torgersen. Analysis of the reduced data confirmed the initial hypothesis that varying the regularization parameter in the deconvolution step of the PDS algorithm introduces bias in estimation of the corresponding turbulent wavefront. Further, it was noticed that the relative size of the object had an effect on which turbulence mode was estimated with the most error: For compact objects, the largest estimation error was observed in lower modes; for extended objects, the largest bias was observed in higher modes.

5.12 Polarimetric Imaging

Polarimetric imaging and polarimetry have great potential to augment conventional imaging SOI and provide another facet of NISOI. Imaging polarimetry with conventional instrumentation can be difficult under the best conditions and nearly impossible under the dynamics of observing LEO satellites; this is due to the difficulty in registering intensity images taken through different polarization filters. Not only is light from different field angles (*viz.*, reflected from various components of the satellite) differently polarized (and so not seen in all intensity images), but LEO objects observed in a small field are subject to atmospheric turbulence noise and jitter. An innovative new technology to mitigate these problems is the Ortho-Babinet Polarization Interrogating (OBPI) filter. Tyler was awarded funds to procure one of these devices, and made several extended trips coordinating the instrument design and future experiments at the Innovative Science and Technology Experimental Facility (ISTEF) on Merritt Island in Florida. In addition to designing a new reconstruction algorithm for the OBPI and analyzing sensitivity, he derived sampling requirements for the OBPI detector array. These sampling requirements allow proper design of the instrument for the variety of telescopes on which it will be used (including, it is hoped, the 3.6-m AEOS at the MSSS).

Dr Tyler has led the development of the polarimetric imaging system at ISTEF. The system consists of an innovative interferometer that encoded the polarization state of incident light as fringe modulation of the observed scene. This imaging polarimeter was procured under an AFOSR DURIP grant. The entire system, including unconventional optics and an electron-multiplying CCD camera, was fully characterized in the ISTEF lab. Unexpected interference phenomena were explored and a calibration algorithm developed to remove it. Full calibration procedures were developed for operational use, and optical and mounting components were developed for use at the ISTEF telescope. Data was collected at ISTEF using two systems. The first consisted of a 5" Questar telescope. This system was mounted on the 20" ISTEF Graz telescope and aligned by ISTEF staff for tracking of aircraft and orbiting satellites. ISTEF operators and technicians supported first-ever collections using this system, including video-rate transient polarization event imaging, something impossible with conventional imaging polarimeters. To demonstrate tracking, Dr Tyler and ISTEF staff collected polarization images of aircraft passing over the site, both at cruise altitude and in the arrival pattern for the Orlando airport. The second system involved a substantial hardware modification in the ISTEF machine shop, allowing the light from the 20" telescope to feed the polarimeter. The second configuration was designed to increase the sensitivity of the instrument for tracking observations of satellites. Although several attempts were made to observe satellites with the second system, bad weather and computer malfunctions unfortunately delayed observations, and PRET funding ran out before we could obtain this data. The data that have been collected, along with simulations, will be used for Mr Murali's doctoral dissertation.

5.12.1 ISTEF's Subtask – Support and Development of OBPI and Target Observation

This subtask was performed by the Innovative Science and Technology Experimentation Facility (ISTEF) in support of Dr. David Tyler's development and testing of the OBPI instrument during his visits to ISTEF. Towards the end of the period, ISTEF personnel participation increased through significant optical design, adaptation of the sensor to the Graz main optics, observation planning, and operation of the sensor during data collections. Reduction and analysis of OBPI data was not included in this task.

ISTEF provided laboratory space for modification of the prototype sensor by Dr. David Tyler, which included installation of a new Andor iXon camera, alignment, polarization tuning, and calibration data collection. ISTEF personnel assistance included fabrication of optics mounting hardware, such as adaptation of a translation stage to the re-imaging optics. ISTEF personnel also fabricated a custom glare stop to Dr. Tyler's specifications for mounting within the iXon camera, to eliminate internal reflection of strong signals.

ISTEF assisted in creation of a small portable polarization calibration source by adaptation of an old 1" aperture integrating sphere to a battery powered lamp. It provided adaptor hardware and assisted in mounting of the OBPI optical rail to the Graz telescope for observation of multiple targets. Personnel assisted observations through operation of the Graz optical mount, and suggestion of targets of opportunity. Targets evolved from static pointing at vehicle traffic across the river, to aircraft, and culminated in pass prediction and tracking of satellites during terminator illumination conditions. Subsequent to Dr. Tyler's determination that the Questar optics did not provide sufficient light gathering power for observation of satellites, ISTEF proposed use of the Graz 20" aperture telescope. After consideration of several configuration options, relay optics were designed and evaluated using Zemax optical CAD software, with performance predictions provided to Dr. Tyler for approval. The relay optical system and mounting hardware were constructed utilizing ISTEF stock components, with the exception of one critical lens, which was procured by Dr. Tyler. ISTEF personnel assembled, aligned, and tested the relay system using a standard camera, demonstrating the system met performance expectations.

ISTEF personnel then transferred the OBPI components to the new Graz mounted and aligned optical rail, checking the alignment of each component. They then operated the OBPI through a series of alignment adjustments and Dr. Tyler's fringe balancing procedure, and provided example images to Dr. Tyler for evaluation. Following Dr. Tyler's target priorities, ISTEF personnel then proposed and performed a series of observations in the Graz 20" configuration, including aircraft, stars, planets, and satellite terminator passes.

The cooling fan built into the iXon camera did not provide sufficient cooling to operate the sensor, EM amplification, and TE cooler during summer daytime ambient conditions in the Graz dome. Care was taken to close the shutter and turn off the EM gain and TE cooler when the temperature range was exceeded. This problem was exacerbated when the configuration was changed to the Graz 20" telescope, requiring a light-tight box to be constructed around the entire OBPI and relay optics.

The solution consisted of three parts. First, a fan was adapted to the box, positioned in front of and supplying external air to the iXon fan at a significantly higher flow rate. Secondly, the OBPI sensor was aligned and focused during dusk or dawn hours where cooler ambient temperatures allowed continuous operation. Third, for daytime observations the iXon was powered up and chill down started five minutes before the event to be observed, which provided enough operational time before the TE cooler was overcome.

It is recommended that the iXon camera be replaced with a more rugged unit before significant summer daytime observations are attempted. The ISTEF Hammammatsu camera, which utilizes the same FPA, may be considered with further evaluation of the control differences.

Pre-dawn terminator satellite passes and dawn/early morning aircraft were routinely observed with little interference from weather or clouds. Daytime satellite passes were observed through broken clouds, but restricted to short time spans of single passes by camera cooling limitations described above. Evening terminator passes were infrequently attempted due to weather predictions that were often wrong. It is recommended that future summer evening collections be attempted utilizing the time proven rule of thumb that you must schedule and attempt three collections to get one good set of data.

The length of the assembled OBPI crystal, re-imaging optics, and camera prevented normal mounting behind the telescope back plate. A relay system was designed, consisting of two folding mirrors and two lenses, allowing the OBPI to be mounted on an optical rail along the top side of the telescope tube (Fig. 1). The design was evaluated using Zemax optical CAD software, yielding performance predictions. The predicted images were provided to Dr. Tyler for approval.

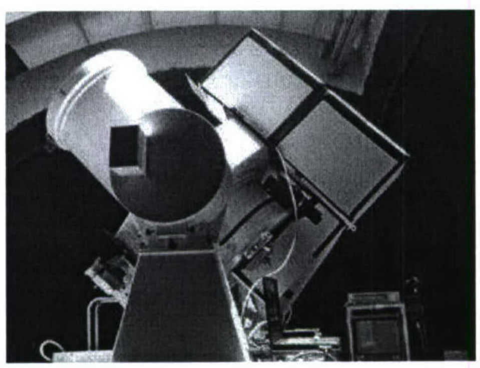

Figure 1: OBPI and Enclosure on Graz Telescope

The configuration within the top enclosure is shown in Figure 2. A mounting adaptor was fabricated to fix optical rail to the side of the telescope, and included adjustments to allow alignment of the optical rail to the relay optical axis.

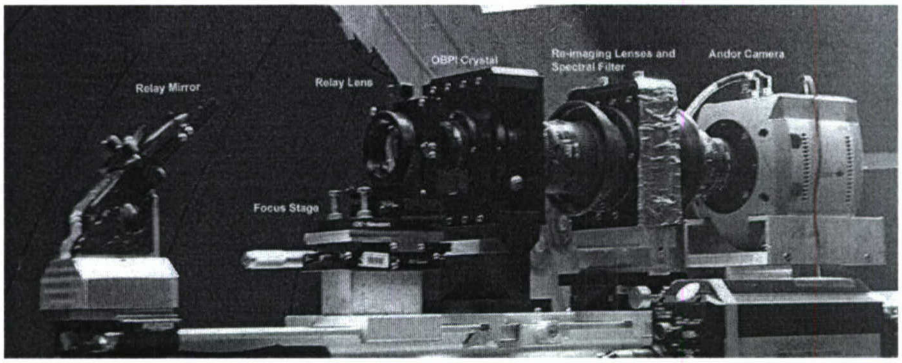

Figure 2: OBPI Optical Rail Assembly with Graz Relay

Left to right the major components are the second folding mirror, second relay lens with focus stage, OBPI crystal holder, re-imaging lens, spectral filter, re-imaging lens, and Andor camera. A hole was milled through the optical rail under the folding mirror to provide for the optical path from below. Lens and mirror mounts provided adjustment in translation as well as tip-tilt.

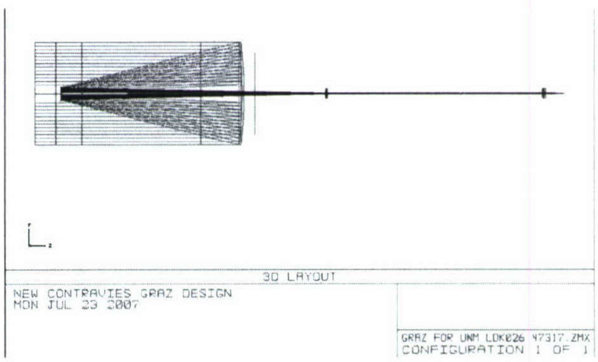

Figure 3: Layout of the relay lenses in Zemax. This view does not illustrate the two folding mirrors used to direct the optical axis to the top of the telescope structure.

The following two figures show the PSF Cross Section and the Geometric Encircled Energy, and thus provide predicted performance measures for the Graz main telescope and the relay system at infinity focus produced by Zemax. Aberrations increased significantly away from infinity focus, yielding visible distortions when focused at 8 - 10 km to observe towers and ships across the river.

5.13 High-Performance Computing

Borelli has continued and completed the development of a parallel version of the Physically Constrained Iterative Deconvolution (PCID) code, being transitioned to operational use at the MSSS. She added to her original innovations by working with Jefferies to parameterize the aberrating wavefront in terms of Zernike polynomials in pupil space, a much more efficient basis than the phase at individual sample points in the pupil. Tyler and Borelli also published a refereed article

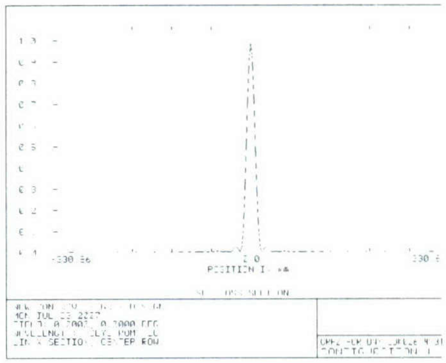

Figure 4: PSF Cross Section

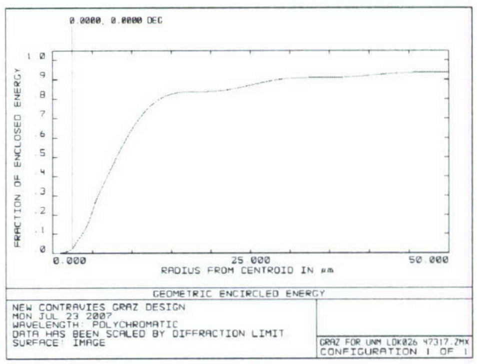

Figure 5: Geometric Encircled Energy

[2] describing an innovative parallel algorithm for bispectrum speckle imaging with large-format detectors.

5.14 AO-Compensated Masked-Aperture imaging

Masking off part of a telescope pupil to mitigate atmospheric turbulence noise was first used to generate high-resolution astronomical images in 1983; but the technique was also used to generate a series of results in the 90's and as recently as 2002. Aperture masking has never been tried with adaptive optics (AO) to reduce residual turbulence or increase measured SNR beyond the maximum available with AO alone, except in simulation. Tyler has renewed investigation of this technique, with new simulations that show encouraging results. The DURIP-funded Space Surveillance Simulator (the "S-Cube") (previously at Oceanit Laboratories' Maui office but now at the IfA, U. Hawaii) includes a wavefront sensor and DM as well as a spatial light modulator (SLM) to create artificial turbulence in the lab. A second, large-format SLM is on long-term loan to Oceanit, and this SLM can be used to impose a mask in the pupil of the S-Cube.

5.15 Optimal Imaging Exposure Time for AO Imaging

Current practice with AO systems is to expose the imaging camera to limit the noise source to the sky background; however, to optimize the Fourier SNR (and thus, the collected information), one must account for the atmospheric turbulence noise uncompensated by the AO system. Longer exposure times allow more light to be collected, but also integrate more turbulence noise. Tyler has shown, using data collected at the MSSS 3.6-m AEOS telescope, that the optimal exposure time is a function of the degree of AO compensation. The goal of this program is two-fold: First, to predict optimal exposure time as a function of data available to the AO operator, such as the wavefront sensor SNR; second, to put the experimental work on a firm theoretical footing. To address the first goal, Tyler is collaborating with Michael Lloyd-Hart at the University of Arizona's Steward Observatory. This collaboration has already yielded some data from Steward's 6.5-m MMT telescope and its adaptive-secondary AO system. To address the second, Tyler is collaborating with Brent Ellerbroek of NOAO's New Initiatives Office.

5.16 Unified approach for the blind restoration of imagery obtained through atmospheric turbulence

A large number of blind deconvolution algorithms have been proposed for the restoration of imagery obtained through atmospheric turbulence. Most of the differences in these algorithms lie in details such as which domain (image or Fourier) is used to model the target object and atmospheric point-spread functions, what types of prior knowledge are enforced and what types of cost function and regularization are used. Typically, each algorithm is successful for a limited range of observing conditions and/or type of target and it is often unclear which algorithm is appropriate for a given data set.

The primary goal of the U. Hawaii based PRET sub-group consisting of Profs. Jefferies, Hope, and Ms. Giebink was to continue developing our "toolbox" of methods for blind deconvolution and to use this toolbox to determine a well-defined approach for ascertaining which tools should be used for any given imaging scenario. A secondary goal was to build a flexible platform for research into new methods for blind restoration with the view that, once the new methods are proven, the relevant code can be easily transitioned into the PCID algorithm.

To facilitate expansion we used an object-oriented approach to the coding of the toolbox ("Kahuna"). To ensure forward compatibility with upcoming computer architectures we developed our code to run on minimal-kernel operating systems. The toolbox runs on both serial machines and parallel machines. It has been successfully run on Cray XT3 machines such as the Sapphire at ERDC MSRC and on Dell PowerEdge 1955 such as Jaws at MHPCC.

The tools in Kahuna include those that are currently implemented in the PCID algorithm (with the exception of Tikhonov regularization) along with

- Ability to model the target object in Fourier domain or (for multi-frame data sets) via a Wiener filter re-parameterization
- Ability to enforce spectral holes constraint on object and PSFs (multi-frame data sets only)
- Choice of additional basis function: Disk Harmonic Functions
- Ability to process simultaneous, multi-wavelength data sets (wavelength diversity)

- Spatial and temporal correlation of wave-front amplitudes and phases

A restoration algorithm is generated by selecting the appropriate tools from the toolbox. Our research shows that the correct selection of tools is obtained by following three simple guidelines: (1) use as many physical constraints as the data allow, (2) use the minimum number of variables that is consistent with the information in the data and (3) provide the best possible initial guesses. Using this recipe we have been able to obtain successful restorations for a wide range of imagery. The last guideline is particularly important when dealing with large ensembles of imagery where the number of variables can run into the millions.

Here we show three examples of research projects addressed using Kahuna. The first and last examples demonstrate potential improvements for the imaging program at AMOS. The first is an upgrade for the PCID algorithm (add Fourier domain model for object and spectral hole constraint); the second is a suggested observing strategy and upgrade to PCID (wavelength diversity).

Figure 6 shows the restoration of the first resolved imagery of a geostationary target (ANIK F2 communications satellite) as obtained using both the PCID algorithm and the Kahuna toolbox. The main improvement seen in the latter comes from being able to circumvent the problems associated with the systematic noise that is present in the raw data (due to problems in the electronic readout of the CCD camera) by modeling the object in the Fourier domain. Some additional improvement is obtained through the use of a "spectral holes" constraint. Interestingly, the poise of the satellite, as determined from the restored Kahuna image, agreed to within 1 degree of its expected value based on the time and location of the observations.

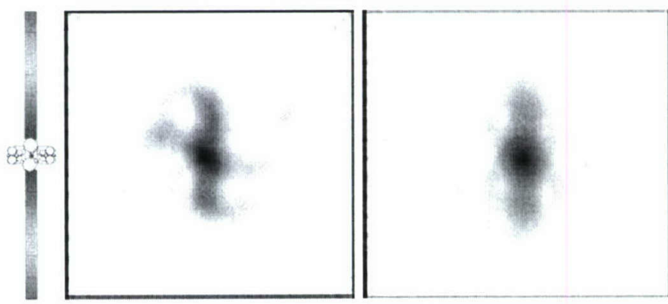

Figure 6: ANIK F2 communications satellite. Schematic from Boeing web site (left) restored image using PCID algorithm (middle) and restored image using the "Kahuna" toolbox.

This work [15] provided the seed for a study of the detection limits for potential micro-satellite companions of satellites in geosynchronous orbit. The simulations were designed to be representative of what can be achieved with current observing capabilities and modeled AO-compensated data at 1.6m as obtained with the 6.5m MMT telescope under median seeing conditions at Mount Graham, Arizona. The results, which show that we can expect to see a 30cm x 30cm object at a distance of 100m from the primary satellite (see Fig. 7), have been of interest to Air Force Space Command (AFSC) and our group has been in discussions with AFSC personnel with regard to future tests of the restoration techniques that were used.

The last example (Fig. 8) shows that it may be possible to obtain high-resolution viewing of targets at visible wavelengths using the 3.6 m AEOS telescope. Normally, successful imaging at visible wavelengths is restricted to rare periods when the turbulence is extremely benign (r_0 [0.5 μ

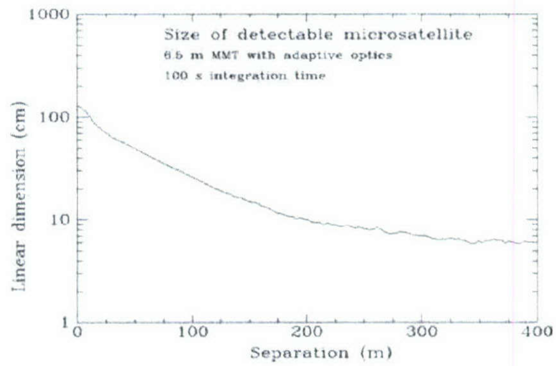

Figure 7: Detection limits for micro-satellites in geosynchronous orbit.

m]>30 cm). However, if a second (simultaneous) data set is available at an infrared wavelength, then a "common optical path difference" constraint can be used, along with a spectral holes constraint, to leverage a high-quality restoration at the shorter wavelength during less than pristine conditions.

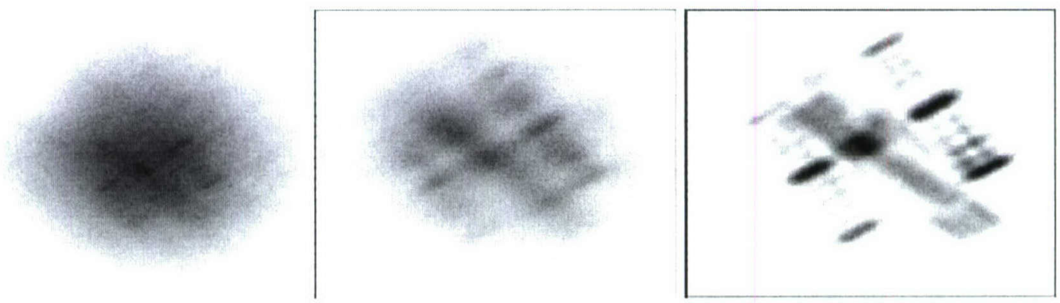

Figure 8: Simulated AO-compensated image of the Hubble Space Telescope as viewed at $0.4\mu m$ under ($D/r_0 \sim 45$) conditions (left), the restored image using the PCID algorithm (middle) and the restored image using Kahuna to process the multi-wavelength data with spectral holes and common optical path difference constraints.

5.17 Evaluation of the effects of finite sample size on the computed statistical information in a recorded image

An important problem in imaging is the assessment of image quality. Various metrics for assessing the image quality exist, such as the log-likelihood function, the log-posterior function and the residual error squared norm. However, these methods are subject to noise amplification and the latter two depend on detailed prior knowledge about the object that is rarely available. A more useful approach perhaps is the use of statistical prior information about the object.

This approach has been espoused in the context of the PRET project by Profs. Prasad and Hope. Here they computed errors in the numerical calculation of information when finite sample size is the main limiting factor, as would be true in most practical situations.

In the framework of statistical information the object and image scenes that belong to statistical ensembles. These ensembles are characterized by the individual, joint and conditional probability density functions (pdf's). The mutual information (MI) is the information successfully transmitted by a system. When computing MI one chooses some object and image attribute of interest. The MI conveyed by image attribute b about object attribute a is,

$$\begin{aligned} MI(a;b) &= H(a) - H(a|b) \\ &= H(b) - H(b|a). \end{aligned} \tag{1}$$

Here $H(a)$, $H(b)$ and $H(a|b)$ are the self and conditional information entropies in the object and image ensembles, defined as the averages

$$H(a) = - < \log_2 p(a) > \text{ and } H(a;b) = - < \log_2 p(a|b) > \tag{2}$$

and the averages obtained from these by interchanging a and b. The quantity $p(a)$ is the (unconditional) pdf for the object attribute a and $p(a|b)$ its conditional pdf for the attribute a, conditioned on the detection of a particular image attribute value b.

When $p(a)$ is not known or is cumbersome to evaluate a histogram estimator approach using a finite sample of object scenes can be used to evaluate the probability. In such an approach an ensemble of high-resolution images, e.g. of ground scenes is used to compute an empirical probability distribution for the object attribute values. Each scene in the object ensemble is imaged in simulation to provide a corresponding ensemble of degraded image scenes. By evaluating the histogram-based estimate of the probability for each of the attributes one could evaluate the mutual information, $MI(a;b)$; however, due the finite sample size there will be a bias and variance associated the information estimate.

The main goal of the work was to numerically evaluate these errors and determine if a more robust approach was possible. An example of the results obtained, for a single random variable, is shown in Fig. 9. One can see that as the sample size increases the bias error and the standard deviation in the MI estimate decreases.

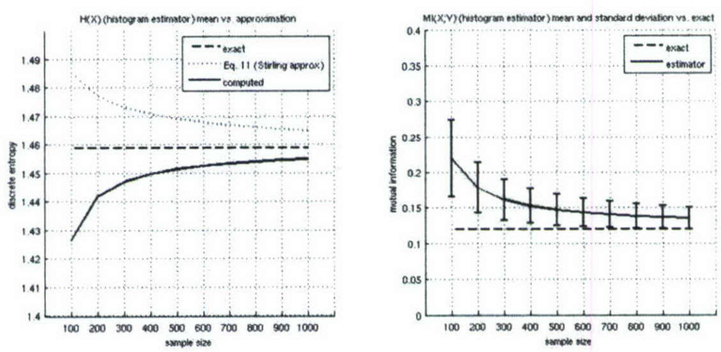

Figure 9: On the left is the mean information entropy (solid line) for a random variable plotted as a function of sample size, the differential entropy (dashed line), or the entropy in the limit of an infinitely small bin size and an approximate expression (dotted line) for the mean entropy. On the right is the mean value with the associated standard deviation plotted as error bars.

In the context of imaging we are interested in computing statistical information for set of parameters that describe the scene. This requires us to compute information for random vectors, which can be a very formidable if not impossible task using a histogram to estimate the probability. As an example if one was to evaluate the entropy for an 8-dimensional probability function using a histogram with a 100 bins along each dimension, the number of bins would be 10^{16} and the sample size required to fill these bins would be quite large. In such a regime the histogram estimator is of limited use.

Consequently, we investigated [16] new Monte-Carlo methods for computing information entropy that are less sensitive the dimensionality of the probability distributions. In the example above we computed the entropy using our new approach with the results plotted as a function of sample size. An acceptable bias and variance is obtained for sample size as small as 10^5 (see Fig. 10). A paper based on this exciting original work is in preparation.

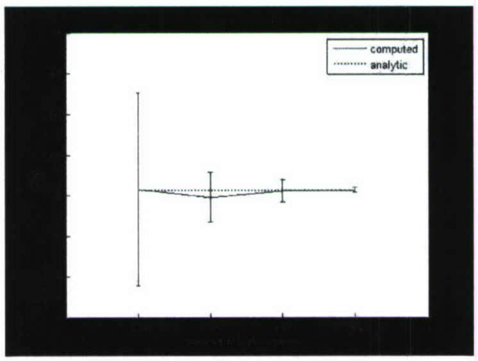

Figure 10: Entropy as a function of sample size, as evaluated by the new Monte-Carlo approach for a Gaussian PDF. The exact analytical value is shown by the dotted horizontal line, while the solid line segments join the numerically evaluated values at three different sample sizes. The error bars represent the variance expected from the numerically evaluated values.

6 Educational/Training Activities

This grant funded research assistantships for two graduate students, Sukumar Murali and Hariharan Muralimanohar. In the final year of the grant, both students passed their PhD comprehensive exams. Mr Murali also worked at Oceanit Labs on Maui during summer 2006, helping with optical system development for PRET-funded Oceanit research. Mr Muralimanohar graduated with an MS in Optical Sciences, with a PRET-funded project comprising his graduate research.

Dr. Hope, now an assistant professor at the U. of Hawaii, worked on the problem of information dynamics in image formation, detection, and processing while a graduate student at the U. of New Mexico under the guidance of Professor Prasad. Although his work was supported mostly independently by a prestigious Michelson Fellowship of the Jet Propulsion Laboratory and NASA, his researches were vital to the development of the information theoretic framework for image assessment that was a critical theme of the PRET project. The impact of his PhD research was quite significant in other ways as well, most notably in helping to create a government funded research program on Maui under the AFRL/DEBI - Boeing LTS umbrella, called Evaluation by

Information Theoretic Analysis (EVITA). This program has had a visible presence on Maui, and while Hope is no longer involved with it, the importance of his initial contributions to the project in terms of developing information theoretic image rating scales cannot be overstated. While a post-doctoral fellow under Profs. Prasad and Jefferies in the years 2005-6, Dr. Hope was supported partially for his work under PRET funding.

7 Technology Transitions

The PRET effort was remarkably effective in leading to innovative technology transitions and federal grants at AMOS/MSSS and elsewhere. In all, nearly \$9M of government investments have resulted either directly or indirectly from these transitions. Of this amount, nearly \$3M can be attributed to 4 transitions that occurred at AMOS/MSSS, namely

1. Development and implementation of Physically Constrained Image Deconvolution (PCID) algorithms; including \$1.5M for the MHPCC/HOKU cluster machine and \$0.7M for PCID automation. More funds are being invested to improve and expand the capabilities of the PCID algorithms, with a "toolbox" approach mentioned earlier in the previous section of this report;

2. Development of the Image Evaluation by Information Theoretic Analysis (EVITA) program funded under a Boeing/LTS task by AFRL – funding to date >\$0.5M;

3. Advanced Imaging Algorithms – a two-year effort funded by AFRL under a Boeing/LTS sub-task between 2004 and 2005 – funding ~\$0.1M; and

4. Space object identification (SOI) using spectral unmixing algorithms, particularly using the concept of non-negative matrix factorization (NMF) – continuing effort that led to collaborations between the PRET, Boeing, and Oceanit researchers and two joint papers – indirect impact on Boeing programs estimated at being greater than \$0.2M.

Other transitions and grant funding that resulted indirectly from the PRET effort but are not connected specifically to the AMOS/MSSS site or programs include

1. Development of a multi-aperture computational imaging system called Practical, Enhanced-Resolution, Integrated, Optical-Digital Camera (PERIODIC) – funded at the level of \$3.5M by the Disruptive Technologies Office (formerly ARDA and soon to be renamed IARPA) during the period March 2005-September 2009. This system is being developed under a multi-institutional collaboration headed by Prof. M. Mirotznik at the Catholic U. of America (CUA) and by Profs. Prasad and Plemmons of the PRET team. The latter provided the initial leadership during the exploratory phase of the project, which is now well into its developmental phase to produce a state-of-the-art multi-modal optical/IR scene interrogation system with dynamically allocatable imaging, non-imaging, and fully integrative resources;

2. Development of algorithms for Next Generation Image Restoration for Space Situational Awareness – explorations of new regularization approaches including spectral holes and temporal correlations of image frames – funding at the level of \$0.6M by AFOSR;

3. Development of the Space Surveillance Simulator (S-Cube) – an experimental system to simulate all aspects of ground-based imaging, including imaging beam propagation, AO, detection, and post-processing for imaging systems such as those at AMOS – funded by two DURIP grants from AFOSR at the level of \$0.77M;

4. Development of the Ortho-Babinet Polarimetric Interferometer (OBPI) for polarimetric measurements – funded by an AFOSR DURIP grant at the level of \$0.25M;

5. Theoretical investigations of sparse representation and compressed sensing of image data – funded by the Army Research Laboratory under an Advanced Sensors Collaborative Technology Alliance (CTA) during the period Oct 2005 – Sep 2006 at the level of about \$0.1M; and

6. Development of Innovative Methods for High Resolution Imaging and Feature Extraction funded by the Army Research Office 2005 through June 2008 at the level of \$0.25M.

8 Enhancement of the Maui Research Environment

Three DURIP awards to PRET researchers in 2004 and 2005 have provided a substantial enhancement to the Maui research environment. The S-Cube will be used by Trex, a subcontractor to Boeing on the MSSS O&M team, to test phase plates. The Naval Research Lab has also expressed an interest in using S-Cube, as has the NSF Center for Adaptive Optics. The S-Cube provides a unique opportunity for space surveillance research without requiring telescope time. New and novel concepts can be evaluated without the expense and complicated logistics of mounting instrumentation on actual telescopes.

The OBPI, after initial testing and observations at ISTEF and the MMT, will be delivered to Maui and evaluated on S-Cube and (one hopes) on AEOS. As described above, the OBPI provides a unique opportunity to enhance SSA research by generating high-resolution polarimetric images free of registration errors.

9 Selected Publications Resulting from PRET Funding Support

A total of 51 publications may be attributed to funding support by the PRET grant over five years. The following is a selection of such publications:

[1] E. K. Hege, S. M. Jefferies, & M. Lloyd-Hart, “Computing and telescopes at the frontiers of optical astronomy”, Computing in Science and Engineering, Vol. 5., No. 6, 42-51 (Nov./Dec. 2003) *Invited Article*

[2] D. W. Tyler & K. J. Schulze, “Fast phase spectrum estimation using the parallel part-bispectrum algorithm,” PASP 116, 65 (2004)

[3] S. Prasad & N. Menicucci, “Fisher information with respect to cumulants,” IEEE Trans. Inform. Theory 50, 638 (2004)

[4] S. Prasad, “Information optimized phase diversity speckle imaging,” Opt. Lett. 29, 563 (2004)

[5] S. Prasad, "Fisher information-based analysis of a phase-diversity speckle imaging system," JOSA-A, Vol. 21, 2073-2088 (2004)

[6] S. Prasad, T. Torgersen, V. P. Pauca, R. Plemmons, & J. van der Gracht, "High-resolution imaging using integrated optical systems," Int. J. Imag. Sys. Tech., 14, 67-74 (2004).

[7] R. Plemmons, G. Golub, & J. Yuan, "Semi-conjugate direction methods for real positive-definite systems," BIT Numerical Mathematics 44, 189 (2004)

[8] J. Bardsley, S. Jefferies, J. Nagy, and R. Plemmons. "A Computational Method for the Restoration of Images with an Unknown, Spatially-Varying Blur." Optics Express, Vol. 14, no. 5, pp. 1767-1782 (2006).

[9] S. Shahnaz, M. Berry, P. Pauca, and R. Plemmons. "Clustering using Nonnegative Matrix Factorization." Information Processing and Management, Vol. 42, pp. 373-386 (2006).

[10] P. Pauca, J. Piper and R. Plemmons, "Nonnegative Matrix Factorization for Spectral Data Analysis," Lin. Alg. and Applic., Vol. 416, No. 1, pp. 29-47 (2006).

[11] Z. Mu, R. Plemmons, and P. Santago, "Iterative Signal and Image Deconvolution for Estimation of the Complex Medium Response," International Journal of Imaging Systems and Technology, Vol. 15, no. 6, pp. 266-266 (2006).

[12] R. Plemmons, "Inverse Problems in Atmospheric Imaging," in Computer Mathematics and Applications: Advances and Developments, Edited by E. Lipitakis, LEA Press, Athens, Greece, pp. 195-204 (2006).

[13] Jefferies, S. M., Lloyd-Hart, M., Hege, E. K., and Georges, J., "Sensing Wave Front Amplitude and Phase using Phase Diversity", Applied Optics, 41, 2095-2102 (2002).

[14] Jefferies, S. M., Schulze, K. J., Matson, C. L., Stoltenberg, K., and Hege, E. K., "Blind Deconvolution in Optical Diffusion Tomography," Optics Express, 10, 46-53 (2002).

[15] Hope, D.A., Jefferies, S.M., Giebink, C., "High-resolution imaging through strong turbulence," Proc. SPIE Vol. 6697, Advanced Signal Processing Algorithms, Architectures, and Implementations XVII (2007)

[16] S. Prasad and D. A. Hope, "Dimensionally Robust Numerical Approach for Computing Statistical Entropies," in preparation.

[17] P. Zhang, H. Wang, R. Plemmons, and P. Pauca, "Spectral unmixing using nonnegative tensor factorization," Proc. ACM, (2007).

[18] D.W. Tyler, H. Muralimanohar, and K.J. Borelli, "The effect of amplifier bias drift on differential magnitude estimation in multiple star systems," Proc. Astron. Soc. Pac., Vol. 119, 183-191 (2007).

[19] D.W. Tyler, "Cramer-Rao lower bound calculations for registration of linearly-filtered images," Proc. of the 35th IEEE Applied Imaging and Pattern Recognition conference, vol. AIPR06, 35 (2006).

[20] T. Torgersen and D.W. Tyler, "Practical considerations in restoring images from phase-diverse speckle data," Proc. Astron. Soc. Pac,, vol. 114, 671-685 (2002).

[21] C. Matson and D.W. Tyler, "Primary and secondary superresolution by data inversion," Optics Express, Vol. 14, pp. 456-473 (2006).

[22] Jefferies, S. M., Schulze, K. J., Matson, C. L., Giffin, M, and Okada, J. 2002, "Improved Blind Deconvolution Methods for Objects Imaged through Turbid Media," in AMOS 2002, AMOS Technical Conference, Kihei HI, September 2002.

[23] Jefferies, S. M., Schulze, K. J., and Matson, C. L., "Blind Deconvolution with the use of a Phase Constraint," in AMOS 2002, AMOS Technical Conference, Kihei HI, September 2002.

[24] Hope, D., Jefferies, S. M. and Hege, E. K., "Diffraction-limited image restoration using a new object prior," in AMOS 2005, AMOS Technical Conference, Kihei HI, September 2005.

[25] Jefferies, S. M. and Giebink, C., "Temporal constraints in the blind restoration of high-cadence imagery obtained through atmospheric turbulence," in AMOS 2005, AMOS Technical Conference, Kihei HI, September 2005.

[26] Bardsley, J., Jefferies, S. M., Nagy, J., and Plemmons, R., "Blind iterative restoration of images with spatially varying blur," in AMOS 2005, AMOS Technical Conference, Kihei HI, September 2005.

[27] Hope, D. A. and Jefferies, S. M., "A new Fourier constraint for multi-frame blind deconvolution of imagery obtained through strong turbulence," in AMOS 2006, AMOS Technical Conference, Kihei HI, September 2006.

[28] S. Prasad, T. Torgersen, P. Pauca, and R. Plemmons, "Integrated Optics Systems for Image Quality Control," Proceedings of the 2002 AMOS Technical Conference, Maui, HI, Sep 2002, on CD-ROM.

[29] S. Prasad, T. Torgersen, V. P. Pauca, R. Plemmons, and J. van der Gracht, "Engineering the Pupil Phase to Improve Image Quality," in Proceedings of the SPIE, Vol. 5108 *Visual Information Processing XII*, edited by Z. Rahman, R. Schowengerdt, and S. Reichenbach (SPIE, Wellingham, WA, 2003), pp. 1-12.

[30] S. Prasad, V. P. Pauca, R. Plemmons, T. Torgersen, and J. van der Gracht, "Deconvolving Space Variant Blur via Pupil-Phase Engineering," invited submission in Optics in Information Systems, Special Issue on Computational Imaging, SPIE Int. Tech. Group Newsletter, Vol. 14, No. 2, 4-5, Aug. 2003.

[31] V. Pauca, R. Plemmons, S. Prasad, and T. Torgersen, "Integrated optical-digital approaches for enhancing image restoration and focus invariance," SPIE Symp. Advanced Signal Processing: Algorithms, Architectures, and Implementations, San Diego, CA, Aug. 2003: Proc. SPIE 5205, 348-357 (2003).

[32] V. Pauca, R. Plemmons, S. Prasad, T. Torgersen, J. van der Gracht, C. Vogel, "An integrated optical-digital approach for improved image restoration," Proceedings of the 2003 AMOS Technical Conference, Maui, HI, Sep 2003, on CD-ROM.

[33] J. van der Gracht, V. Pauca, H. Setty, R. Narayanswamy, R. Plemmons, S. Prasad, and T. Torgersen, "Iris recognition with enhanced depth-of-field image acquisition," Visual Information Processing, Orlando, FL (April 2004): Proc. SPIE 5438, pp. 120-129 (2004).

[34] S. Prasad, V. Pauca, R. Plemmons, T. Torgersen, and J. van der Gracht, "Pupil-phase optimization for extended-focus, aberration-corrected imaging systems," Integrated Signal and Image Processing conference, 49th Annual SPIE Meeting, Denver, CO, August 2004: Proc. SPIE 5559, 335-345 (2004).

[35] R. Plemmons, V. Pauca, S. Prasad, S. Robinson, H. Setty, T. Torgersen, J. van der Gracht, M. Horvath, E. Leonhardt, E. Dowski, R. Narayanswamy, P. Silveira, "Computational imaging systems for iris recognition," Integrated Signal and Image Processing conference, 49th Annual SPIE Meeting, Denver, CO, August 2004: Proc. SPIE 5559, 346-357 (2004).

[36] D. Hope and S. Prasad, "Information-theoretic metrics of image quality in phase-diverse speckle imaging," Proceedings of the 2004 AMOS Technical Conference, Maui, HI, Sep 2004, on CD-ROM.

[37] S. Prasad, "Optical preconditioning and digital image restoration," Unconventional Imaging conference, 50th Annual SPIE Meeting, San Diego, CA, July 31, 2005: Proc. SPIE 5896, 589609-1 - 589609-12 (2005).

[38] S. Prasad, "Digital Superresolution and the Generalized Sampling Theorem," J. Opt. Soc. Am. A, vol. 24, 311-325 (2007).

[39] S. Prasad, "Digital and Optical Superresolution of Low-Resolution Image Sequences," Unconventional Imaging conference, 52th Annual SPIE Meeting, San Diego, CA, July 26, 2007: Proc. SPIE 6712, 67120E (2007).